Chapter 5

FULL-SCALE HEAT RELEASE RATE MEASUREMENTS

by

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The ability to accurately measure the heat being released by items such as burning furniture or industrial commodities, or by entire burning rooms, today is viewed as essential to fire protection engineering. While it is essential today, it is interesting to note that such a capability was not achieved successfully until the early 1980s, although there were some slightly earlier explorations. Indeed, the whole science of fire testing and fire modelling was greatly held back during the 1970s due to the lack of this capability.

EARLY DEVELOPMENTS

Prior to the mid-1970s there was little need to make experimental studies of the details of room fires. Room fire experiments were typically conducted as an adjunct to studying fire endurance. For such purposes, it was necessary to track the average room temperature, since this temperature was viewed as the boundary condition determining what the wall, floor, column, etc., was exposed to. Neither the heat release rate, nor other aspects of the room fire such as gas production rates were of major interest. While as early as 1950, some investigators, in conducting full-scale house burns, did try to study the gas production rates, as a means of determining how early untenable environments might exist [1], there was no great incentive to pursue the topic quantitatively.

The incentive came with the development of the mathematical theories of room fires. These are discussed in detail in Chapter 6. Post flashover room fire theories were being developed throughout the 1950s, 1960s, and 1970s. The more detailed understanding necessary for the pre-flashover portion of room fires was becoming achievable by around 1975.

During the 1970s, however, empirical room fire tests were regularly being conducted at many fire research and testing facilities throughout the world.

Instrumentation typically comprised a multiplicity of thermocouples; several probes where gas samples were extracted; smoke meters, typically located at several heights along an open burn room doorway; heat flux meters located in the walls of the burn room; and, possibly, a load platform. The load platform might register the weight of a single burning item, but was of little use when fully-furnished rooms were tested. Despite the fundamental role of heat release rate in the room fire, there was nò technique available to measure that. Since neither the burning item's mass loss rate nor the air and gas flow rates could, in most instances, be determined, the measurements of gas and smoke concentrations at isolated measuring stations were not of much use in tracking evolution rates.

Two developments needed to be become available before further progress could be made: a robust instrument for measuring flow rates of combustion products; and, especially, a practical technique for measuring heat release rate. A robust instrument for measuring the flow rates of air and gas in a soot-laden environment was first presented G. Heskestad at FMRC in 1974 (Figure 1) [2]. Conventional velocity measurement devices are normally precluded from use in fire applications due to several problems. These include clogging of small orifices (an issue with pitot/static probes) and the inability to properly calibrate for high temperature use (hot wire or disc anemometers). The new 'bi-directional velocity probe' solved these problems of measuring air flow rates in rooms, in corridors, and in smoke extraction systems.

A flow calorimeter for measuring sensible heat could have been proposed as the tool for measuring heat release rates, and, in fact was suggested (see the

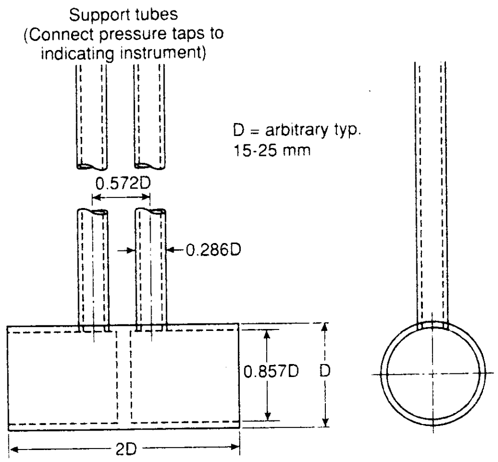

Figure 1. The bi-directional velocity probe

Monsanto calorimeter, below). From the discussion of the bench-scale techniques above, it was known that such a device would not likely be of good accuracy or useability. Thus, by far, the most important development which was needed, however, was the principle of oxygen consumption. The principles of oxygen consumption are covered in Chapter 3. The application of this principle to room fires literally revolutionized the field. Prior to that, the focus was on point measurements. It is adequate to use measurements of temperatures and other quantities at individual locations in a room as a means of verifying a model **if** a near-ideal model is already available. Such point measurements, however, were of limited use in developing and extending the models. With the availability of oxygen consumption-based rate of heat release measurements, for the first time quantitative descriptions of fire output could be made.

ROOM CALORIMETRY

The Monsanto Room Calorimeter

The first attempt to develop some technique for measuring rate of heat release in full scale was in 1978, by Warren Fitzgerald, at Monsanto Chemical [3]. He constructed a small room (2.7 x 2.7 x 2.7 m) instrumented with a large number of thermocouples, located in the gas space, the walls, and the exhaust duct. The room (Figure 2) had a forced air supply of 0.19 m^3/s, from a small 0.15 x 0.15 m supply duct (later raised to 0.26 m^3/s [4]), with another duct used to let out the combustion products. The room was also equipped with a load cell and a port for extracting gas samples. Fitzgerald realized that a simple measurement of temperatures in the exhaust duct would not be sufficient to determine the heat release rate. Instead, he developed a purely statistical method – a correlation was sought between contributions from the various temperature measurements to the heat release rate. The stated capacity was 140 kW, which would not nowadays be considered to be full-scale.

The facility was designed for measuring the burning rate of relatively small, free-standing combustible items. One interesting early measurement attempt in the

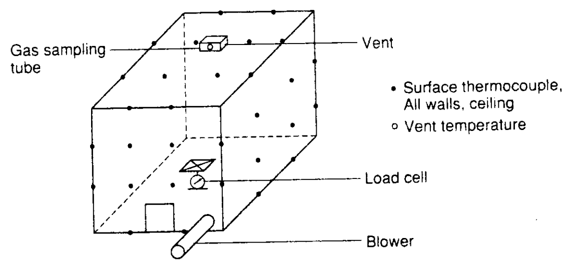

Figure 2. The Monsanto calorimeter

apparatus was on a series of pool fires of three different polymers: polymethylmethacrylate (PMMA), fire-retarded (FR) polystyrene, and non-fire-retarded polystyrene [5]. The investigators tested three pool diameters, 0.3, 0.6, and 0.9 m. Data for the smaller two diameters appeared to show relatively constant per-unit-area rates of heat release, as discussed in Chapter 7. For the 0.9 m PMMA fire, however, the burning rate, per unit area, was much lower, suggesting that a vitiated room condition was already reached. By 'vitiated,' we mean that the flows change so that the fire instead of pulling in primarily fresh air, at 21% oxygen, from the environment, is now pulling in some re-circulated combustion products. Once this happens, the burning rate will tend to drop.

This system has been sporadically in use at the Southwest Research Institute, in San Antonio, Texas. The approach, however, has not been pursued by any other laboratories due to its empirical nature, its limited heat handling capacity, and due to concerns about errors due to varying radiative fractions.

The ASTM room fire test

During the late 1970s and early 1980s a number of laboratories decided on the need for developing a standardized method for measuring heat release rates in rooms, based on oxygen consumption. Unlike the Monsanto test, the concern here was in measuring the burning rate of combustible room linings (*i.e.*, wall, ceiling, or floor coverings), and not furniture or other free-standing combustibles. The original development was at the University of California by Fisher and Williamson [6]. Later, extensive development was also done at the laboratories of the Weyerhaeuser Co., and at NBS [7]. The method, in its simplest form, consisted primarily of adding oxygen consumption measurements into the exhaust system attached to a room very similar to that originally used by Castino and coworkers at Underwriters Laboratories [8], who, however, did not measure heat release rates at all. The room was 2.4 by 3.7 m in size and 2.4 m high, with a single doorway opening in one wall, 0.76 m wide by 2.03 m high (Figure 3). The original studies at the University of California led to ASTM issuing in 1977 a Standard Guide for Room Fire Experiments [9]. The Guide did not contain prescriptive details on room size, ignition source, etc., but was simply a guide to good practice in designing room fire tests of various sorts. The Guide being completed, ASTM then turned to consideration of an actual prescriptive test method. Such a test was published as a 'Proposed method' in 1982 [10]. The 1982 document mandated the above-mentioned room size and also a standard ignition source, which was a gas burner, placed in a rear corner of the room, giving an output of 176 kW. Since the development work at the U. of California with a natural convection exhaust system uncovered problems with it, the actual test specification entailed a requirement to 'establish an initial volumetric flow rate of 0.47 m^3/s through the duct if a forced ventilation system is used, and increase the volume flow rate through the duct to 2.36 m^3/s when the oxygen content falls below 14%.' This specification required a complex exhaust

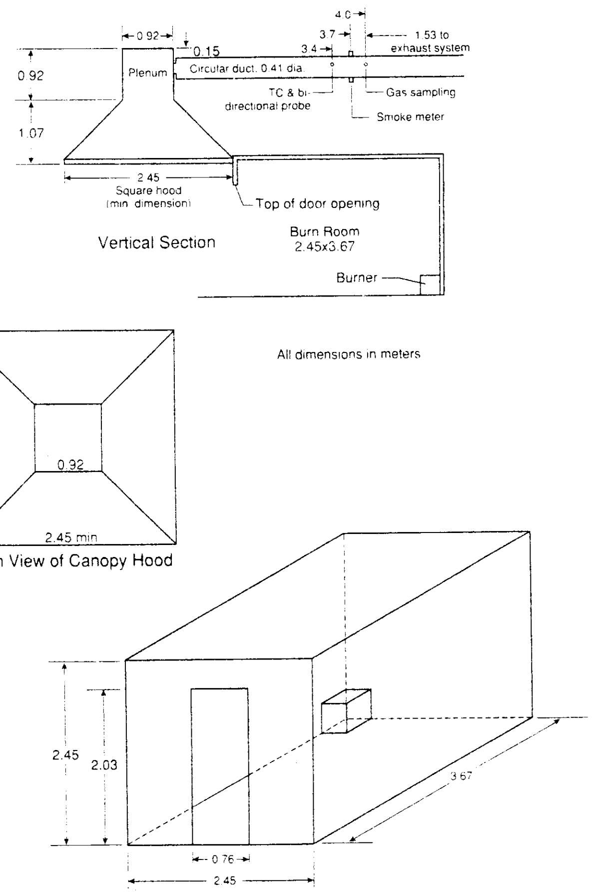

Figure 3. The ASTM room fire test

arrangement, and it is not clear that there were many laboratories prepared to meet it. The proposed method was withdrawn by ASTM; however, variants of this method continue to be used by a number of laboratories. Very recently, an international round robin on this activity has been organized by ASTM [11].

The NORDTEST/ISO room fire test

Following ASTM's hiatus in the development of a standard room fire test, activity was accelerated in the Nordic countries, operating under the auspices of the NORDTEST organization. Development was principally pursued in Sweden, at the Statens Provningsanstalt (SP) by Sundström [12]. The NORDTEST method [13], as eventually published in 1986, uses a room of essentially the ASTM dimensions (Figure 4), 2.4 by 3.6 m by 2.4 m high, with an 0.8 by 2.0 m doorway opening. The exhaust system flow rate capability was raised to a required value of 4.0 kg/s, with the capability to go down to 0.5 kg/s mandated to be available during the early part of the test in order to increase the resolution.

Gas sampling was done similarly as on the Cone Calorimeter: a multiple-hole probe, positioned in the duct opposite to the direction of impinging flow. The rate of heat release computations were, again, done in the standard manner for oxygen consumption calorimetry.

A special concern in the Nordic countries has been the effect of the igniting burner. A parallel project at the Valtion Teknillinen Tutkimuskeskus (VTT) in Espoo, Finland by Ahonen and coworkers [14]developed data on three burner

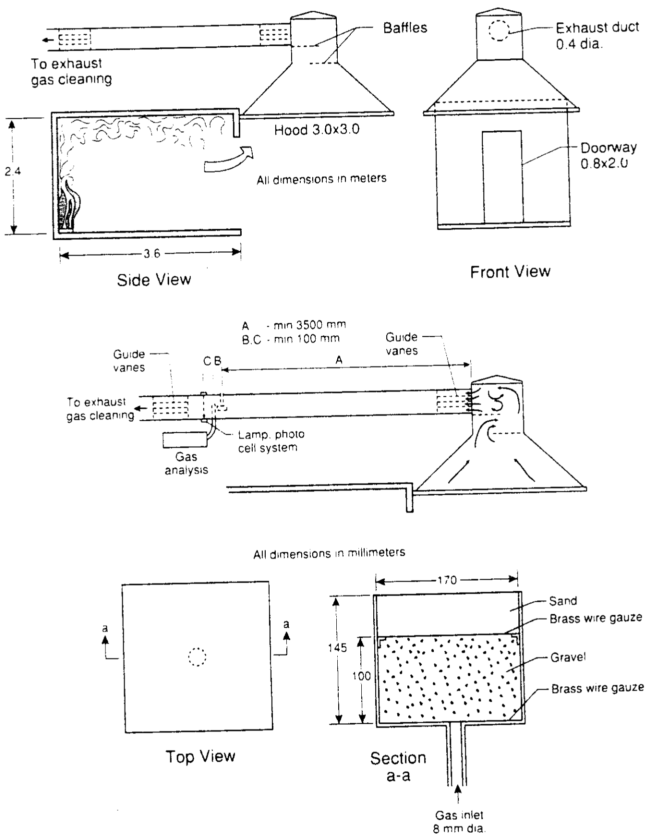

Figure 4. The NORDTEST room fire test

sizes and three burner outputs. The three burners had top surface sizes of 170 mm by 170 mm, 305 by 305 mm, and 500 by 500 mm. The fuel flow rates were 40, 160, and 200 kW. The results that the VTT reported were on chipboard room linings. They found no significant differences at all between the burner sizes. The burner output did, of course, make a difference; however, the difference between 40 and 160 kW was much larger than between 160 and 300 kW. The VTT conclusion was that either the 160 or the 300 kW level was acceptable. The NORDTEST method itself has taken an ignition source to be at the 100 kW level. The 100 kW level was chosen so that the flames would just hit the ceiling; in this manner, tests can be conducted where only ceiling material alone is being exposed and the walls are non-combustible. If no ignition is achieved in 10 minutes, the heat output is then raised to 300 kW.

The NORDTEST room has recently been put forth as an International Standard by ISO (the International Organization for Standardization) [15]; this status has already been discussed in chapter 1. In contrast to the NORDTEST method, however, the ISO version allows different alternative ignition sources to be used.

Other room fire tests

Variants of the above room fire tests have been specified for various purposes. In most cases, the instrumentation used and the measurements made are very similar to the tests already discussed. One slightly different example has been the room fire test specified under California Technical Bulletin 133 [16]. This method is an older variety of room fire test, intended for testing upholstered chairs, where heat release is not directly measured. Unlike other test methods, the California method includes specific pass/fail criteria. It is expected that the California method will eventually be revised to conform more closely to the ASTM method.

FULL-SCALE, OPEN-AIR CALORIMETRY

The most significant efforts in recent years in the area of full-scale test development has gone into developing open-air calorimeters. One might well ask, why if the burning rates in room fires are of concern, is it important at all to make studies under open-air conditions? The reasons have to do with the nature of a room fire during its early stages. It is intuitively obvious that a **very** small fire in a room will behave the same as if it were in the open air (provided, of course, we specify that our open-air conditions are largely wind-free). It is not necessarily intuitively obvious that for larger fires the same statement could be made. Indeed, post-flashover fires can reach a state known as 'ventilation limited.' This means that so much combustible vapours are being liberated from the fuel items that, on the average, all of the available inflowing oxygen is still insufficient to meet the oxygen demands of the fire. This does not quite mean that the combustion gases, if measured, will show exactly zero oxygen. A small amount of oxygen may be measurable in such a 'ventilation limited' fire. It is there because mixing is not perfect, and, therefore, the oxygen was not available to the fire in those locations where it was actually needed. In such a ventilation-limited fire the nature of the combustion will, perforce, be different from that out in the open.

Within these two intuitive limits, in the 1970s it was surmised that serious effects of the room upon the fire would be felt fairly early, and that the utility of open-air calorimetry would, thus, be very restricted. To assess this issue empirically, two series of tests were conducted at NBS where open burning rates were

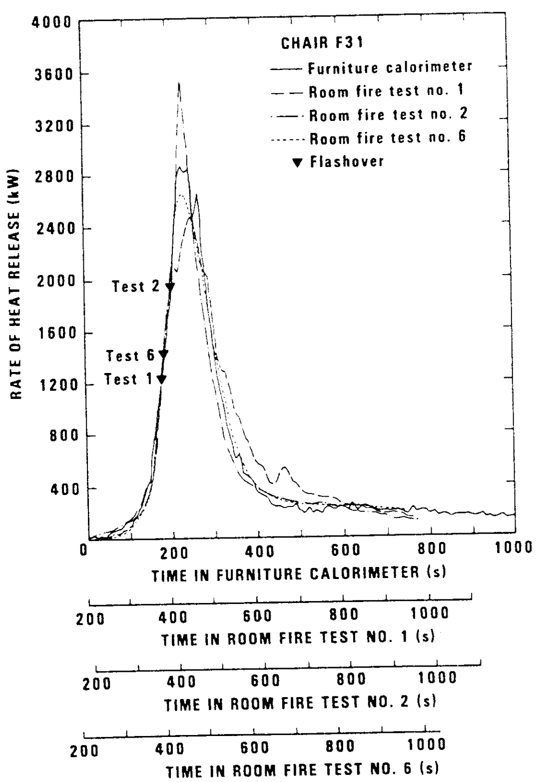

Figure 5. Results for chairs showing similar burning behaviour is obtained in open-air burns and in room fires, even post-flashover, but excluding any post-flashover ventilation-limited fire stage.

compared directly against room fire burning rates. In one test series [17], mock bedrooms were erected. These included a night table, but the dominant fuel item was a bed set. This arrangement of test articles was tested once in the open air, and again in a standard-sized room. The results showed some augmentation of burning rates after flashover, but only by about 15-30%. The second test series [18]involved upholstered chairs and 'two-seaters'. The results typically showed (Figure 5) that for chairs the heat release rates in a room fire were essentially identical to the open burn rates, not only up to flashover, but also after flashover. Again, the stipulation is made that we do not extend this to any post-flashover fire where the burning rates are so large and the ventilation flows are so small that ventilation-limited burning results. These results are, perhaps, somewhat surprising, since it is known that for pool fires there will be a room effect (Chapter 7). The main explanation is that furniture fires are not as 'open' as a pool fire. That is, in a furniture fire, portions of the burning items will be 'viewing' other portions of the furniture assemblage, not just viewing the walls and ceiling.

The conclusions from these studies is that open-air calorimetry would not be appropriate for studying fires on floor, wall, or ceiling linings, where the room geometry is intrinsically bound up with the configuration of the combustible. For most other items which can be viewed as discrete combustibles, however, assessing their rate of heat release (and other fire properties, see Chapter 9) in an open-air environment makes a great deal of sense. The data thus obtained are **universal** — they can be applied to various design problems, short of the ventilation-limited fire conditions. Conversely, any measurements made on room fires may not be expected to be universal, since the burning items may be influenced by other combustibles present, or may lose their meaningfulness once the room fire goes to a post-flashover ventilation limited condition.

The NBS Furniture Calorimeter

The ability to make heat release rate measurements under open-air burning conditions is also rather recent. The current-day full-scale heat release rate methods date to two developments in the early 1980s, one at NBS and the other at FMRC. At NBS, an open-air full-scale calorimeter was built using the concepts of oxygen consumption. The device was termed the 'furniture calorimeter,' since its earliest applications were for the testing of upholstered furniture. The term has since become somewhat misleading, since numerous commodities have been tested in it. Figure 6 shows the first NBS furniture calorimeter [19]. The calorimeter comprised the following main devices:

- a platform-scale type of load cell
- oxygen measuring instrumentation in the exhaust stack
- flow rate measuring instrumentation in the exhaust stack
- a smoke photometer in the exhaust stack
- gas-measuring instrumentation in the exhaust stack
- a radiometer.

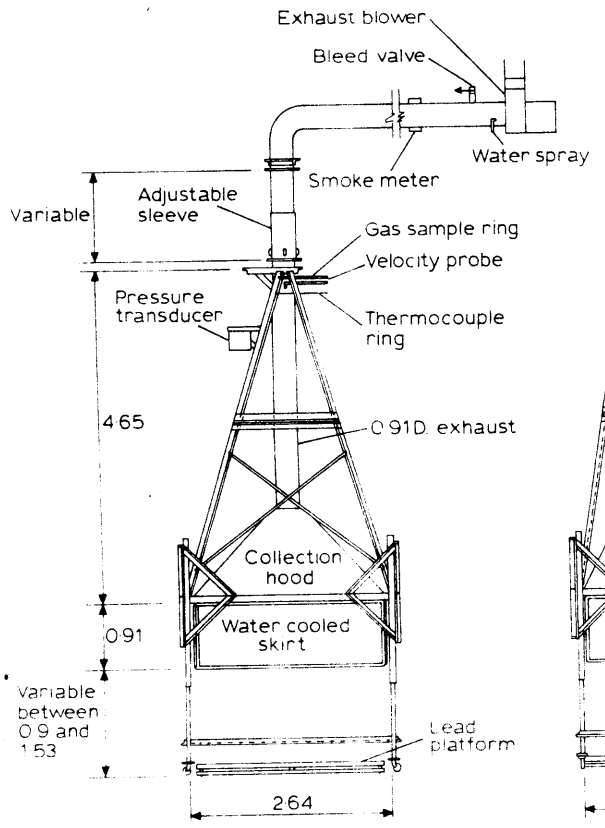

Figure 6. The original NBS furniture calorimeter

The latter was a radiant heat flux meter located 0.5 m above the platform and 0.5 m in front of the burning specimen, intended to assess the potential of the burning item to ignite neighbouring items. Some previous NBS studies on the burning behaviour of furniture [20]had shown that an 0.5 m distance is the most critical for evaluating ignitability of additional room items. Items placed much closer to the original item are likely to ignite by direct flame extension. Items located much farther than 0.5 m away were not likely to be ignited from radiation from the first item alone, and would probably require room flashover to become involved. The oxygen consumption instrumentation is very similar to that employed in the bench-scale (see Chapter 3). A photometer of an incandescent-lamp type was used in the original unit; this has since been replaced with a laser photometer similar to the one provided for the Cone Calorimeter. The capacity of the original version of the Furniture Calorimeter was approximately 2000 kW. To reach this level required a careful limiting of excess air entrained

into the fire plume. For this purpose, a set of water-cooled skirts were provided. These were set low enough to limit the excess air to a quantity which would not overflow the 1.0 m^3/s capacity of the exhaust hood. The original unit ran in a mixed-mode exhaust flow, i.e., the mass-flow rate dropped as temperatures rose, but it did not drop as much as it would under a pure 'fan-law' operation, where the mass flow rate can be computed from assuming that the actual volume flow rate is temperature-independent.

A calorimeter with a 2000 kW capacity could be used to test fast-burning chairs, but would typically not have enough capacity for a sofa. For testing items producing higher heat release rates, a 'large-hood' version of the Calorimeter was implemented. This arrangement received its drawing power from an afterburner assembly, which was designed to exhaust in a constant-mass-flow mode, i.e., changing temperatures did not affect the mass flow rate being exhausted through the system. The large-hood calorimeter has a capacity of 4.2 kg/s of air flow, and has been used to measure specimens releasing up to 7000 kW. The instrumentation and the measurements made are quite similar to the original furniture calorimeter.

From time to time, additional hood systems have been implemented at NBS for different projects. A medium-flow rate implementation, suitable for fires up to about 500 kW, for instance, was configured for studying fire plumes of interest for nuclear winter studies [21].

The NORDTEST Furniture Calorimeter

Since a furniture calorimeter has proven to be one of the most useful ways of characterizing the burning of furniture, it was appropriate that a standard method – not just an experimental technique – become available for it. Researchers at the Statens Provningsanstalt (SP) in Sweden considered the original NBS calorimeter, modified it slightly [22], and developed it into NORDTEST standard NT FIRE 032 [23]. The method (Figure 7) as specified in the standard, uses a wood crib ignition source; NORDTEST are considering the possibility of replacing it with a gas burner. The measurements made and the means of data analysis are very similar to the ones for the NBS Furniture calorimeter.

ASTM has recently been considering adopting a version of the NORDTEST furniture calorimeter; the main change under discussion is the use of a gas burner as the ignition source.

The FRS natural-convection furniture calorimeter

Currently, the main furniture calorimeter in use at the Fire Research Station (FRS) in England is a unit made to the NORDTEST specification. Prior to

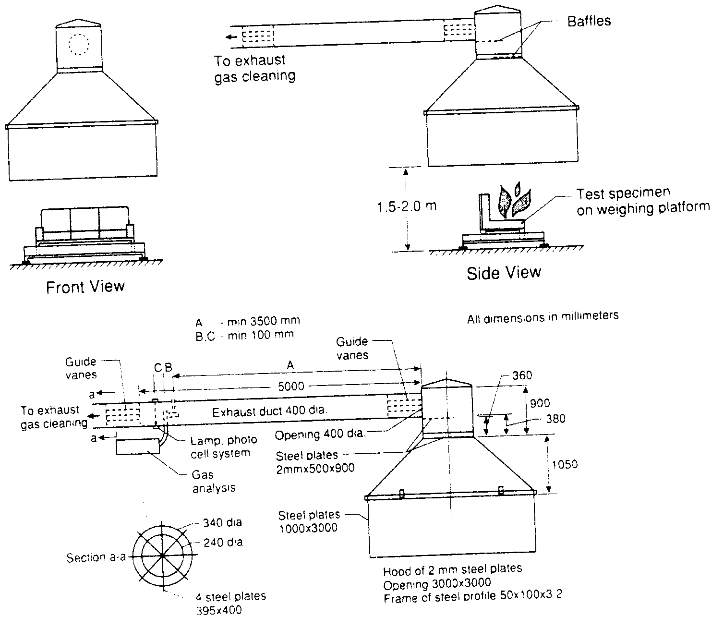

Figure 7. The NORDTEST furniture calorimeter

constructing this calorimeter, the FRS developed a calorimeter which was natural-convection operated. The calorimeter (Figure 8) did not have an exhaust fan. Instead, the chimney effect was used for exhausting the combustion products. Otherwise, the instrumentation used and the data derived were very similar to those for the NBS or the NORDTEST calorimeters. The capacity of a unit such as this is somewhat hard to describe. Unlike the fan-exhausted calorimeter, where the exhaust (volumetric) rate is fixed by the fan capacity, the drawing capacity of a chimney depends on the temperature that it is heated to. Problem with overflow can more readily occur at very small flows, which occur at the start of a fire, when the chimney is not yet pre-warmed, rather than later in the fire, when the chimney is hot. This calorimeter was used by FRS to collect a large amount of data on upholstered furniture and other commodities. FRS still maintain this original calorimeter, although most of the current testing has been moved over to their NORDTEST unit.

The Underwriters Laboratories furniture calorimeter

The Underwriters Laboratories (UL) have recently introduced a furniture calorimeter [24]. This is very similar to the NORDTEST unit, with the exception that measurements of smoke and some combustion gases has been omitted and an igniting crib of a somewhat different design has been specified.

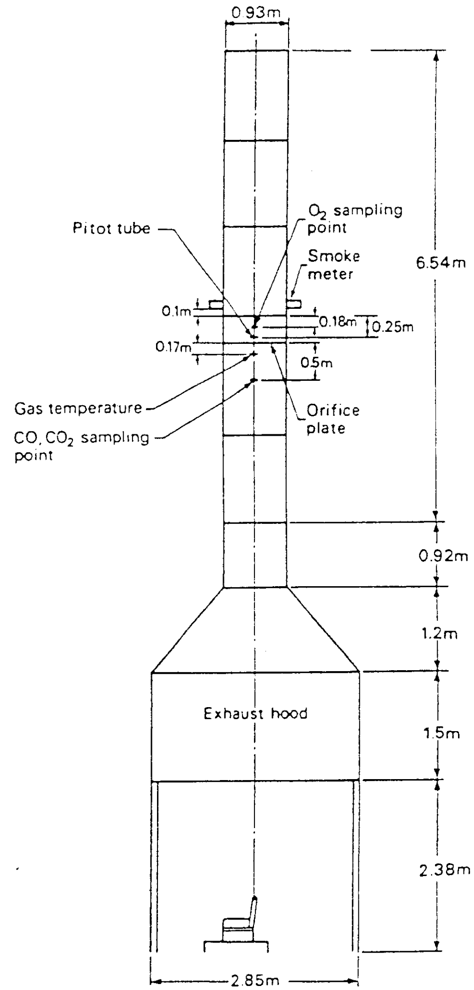

Figure 8. The FRS natural-convection furniture calorimeter

Additionally, there are specific pass/fail criteria provided for the rating of upholstered furniture.

The FMRC Fire Products Collector

At FMRC, Gunnar Heskestad designed a large-scale heat release rate calorimeter, intended for measuring the burning rate of stored commodities [25]. This calorimeter (Figure 9) uses an exhaust duct with a round opening of 6.1 m

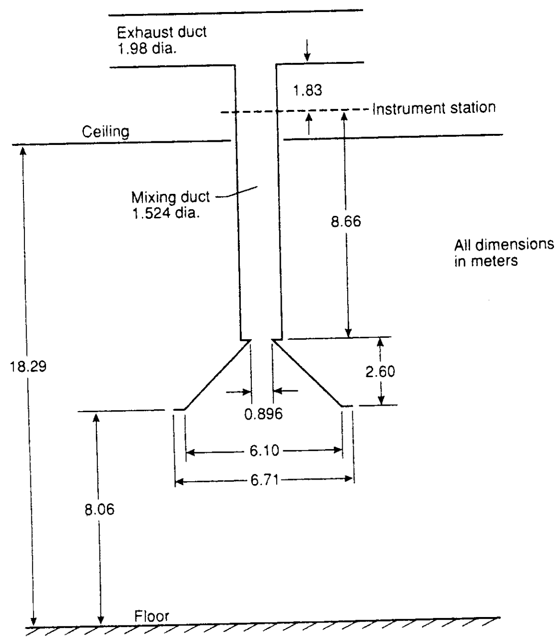

Figure 9. The Factory Mutual fire products collector

diameter. Due to its intended purpose of being used over a warehouse-type stack of commodities, the height of its opening is 8 m above the floor. The flows are channelled through a 1.5 m exhaust duct, and are exhausted at a maximum rate of 30 kg/s. Thus, at first glance, it would appear that the capacity of this device was some 7 times that of the largest version of the NBS instrument. In actual use, however, freeboard heights have to be considered, as well (see below). Thus, under normal operating conditions, FMRC have considered their apparatus to be of around 5 MW capacity.

The determination of the rate of heat release is done by either oxygen consumption calorimetry, or by using CO_2 production measurements, much as implemented on the bench-scale FMRC Flammability Apparatus.

The SP Fire Products Collector

A very similar large-scale heat release rate calorimeter to the one at FMRC has been built at Statens Provningsanstalt (SP) for measuring the HRR of warehouse-type stacked commodities. It has also been used for measuring burning behaviour during application of water to study suppressibility of various warehouse commodities. Comparative testing on some commodities has recently been

conducted by FMRC and SP which showed very good reproducibility between the test results on the two installations [26],[27].

APPENDIX: FLOWS AND CAPACITY IN OPEN-AIR CALORIMETRY

The exhaust system used for removing the products (here, we will take the term combustion products to include both the stoichiometric products of combustion, and also any additional excess air being entrained through the system) has the basic requirement that it should not overflow. Both open-air burning of items and the measuring of room fires by collecting their products require that an exhaust hood be erected and drawn upon in such a way as to avoid overflow. Overflow can occur if the hood size is too small; in that case, the fire plume below may be too wide by the time it reaches the hood in order to be contained by its sides. More serious, however, is a problem of insufficient flow capacity. A hood may be of adequately wide dimensions. If the flow rate that can be put through it, however, is less than the flow rate of heated gases reaching it, the hood will overflow. Any overflow, of course, is not measured, and may also present a health hazard to the laboratory occupants. Thus, the design of full-scale calorimetry devices is vitally concerned with providing adequate flows.

Exhaust systems may be of several different types. Mechanically the simplest is a natural-convection chimney. In a chimney, the mass flow rate $\dot{m}$ (kg/s) will be roughly

$$\dot{m} = A\sqrt{2gH(\rho_o - \rho_f)\rho_f} \qquad (1)$$

or, a volume flow rate, $\dot{V}$ (m^3/s), of:

$$\dot{V} = A\sqrt{2gH(\rho_o - \rho_f)/\rho_f} \qquad (2)$$

where A is the chimney cross-section area (m^2), ρ_o is the ambient density (kg/m^3), ρ_f is the average gas density in the chimney, g is the gravitational constant (9.8 m/s^2), and H is the chimney height (m). An exhaust system of this kind was used for the first room fire experiments at the University of California. This proved not to be very satisfactory for two reasons: (1) the velocities are relatively very low, requiring an impractical duct diameter – several meters for venting a small room – to achieve sufficient flow without spillage; and (2) the chimney has no natural draw until it has been heated up. The latter means that very rapidly developing fires may overflow the system at the start of a test, even though much larger quantities can be successfully carried away later in the test.

The next most common arrangement is a system which operates by 'fan law.' What this means is that typical exhaust fans, of centrifugal and other varieties, have the property that when the temperature of the gas changes that the actual volume flow rate is invariant. The mass flow rate, of course, then drops proportionately. Such an operation is not always desirable for a full-scale calorimeter, since it means that as the fire gets the hottest and the largest amount of gases needs to be moved, the capacity becomes the lowest.

Finally, there is the operation in constant-mass mode. The largest version calorimeter at NBS, for example, obtains its drawing power from an afterburner system, the mass-flow rate of which is unchanged by the temperature of the gases being collected. Thus, true constant-mass operation results. Constant-mass operation is also possible in simple fan-driven systems, where the exhaust arrangement is such that the gases have cooled down completely to room temperature before they reach the fan.

Mixed-mode operation is also possible. The most typical would be a tall, vertical initial collection duct then going into a centrifugal fan. The tall duct will function as a natural-draft chimney, modifying the characteristic of the fan. The drop in mass flow rates with rising temperatures will not be as severe in such a design, since it will be partially compensated by the increased pressure head of the natural draft.

What has to be considered next is the amount of products to be collected. Certainly to be collected is the stoichiometric amount of the combustion products. This could only be done, however, in a fully-enclosed furnace, where air flow arrangements would be made to prevent excess air entrainment. In open-air calorimetry, however, the fire as it burns entrains a large amount of excess air. According to equations given below, a fire plume in still air, by the time the uppermost tip of the flames is reached, will have pulled in about 18 times the stoichiometric amount of air. Consider, now, what happens if the bottom of the collection hood is placed at exactly the height of the intermittent-flame zone tip. Then the depletion of oxygen will be one part in 18, giving a minimum oxygen reading of 20.95(17/18) = 19.79%. Since this is what is happening at the **peak** burning of the fire, the remaining burning time will show a much lower oxygen depletion. Accurate oxygen consumption measurements become difficult under such conditions. What is the source of the problem, then? The problem is that setting the height of the hood at the tip of the flames is not a good practice. The air entrained into the plume increases with increasing 'freeboard' height, where we measure freeboard as the height between the base of the fire and the lip of the hood. The flow at the base of the fire consists of the fuel vapours only. With increasing height, an increasing amount of air is entrained from the environment. The amount that is pulled, in addition to varying with the height, also depends on the heat release rate, Q (kW). McCaffrey [28]has provided a series of equations for evaluating this flow,

Continuous flame zone: $0 < z/Q^{2/5} < 0.08$

$$\dot{m}/Q = 0.011(z/Q^{2/5})^{0.566} \quad (3)$$

Intermittent flame zone: $0.08 < z/Q^{2/5} < 0.20$

$$\dot{m}/Q = 0.026(z/Q^{2/5})^{0.909} \quad (4)$$

Plume zone: $z/Q^{2/5} > 0.20$

$$\dot{m}/Q = 0.124(z/Q^{2/5})^{1.895} \quad (5)$$

where $\dot{m}$ is the mass flow rate (kg/s), and z is the freeboard height (m). The plume zone corresponds to heights above the top of the flame tip; practical freeboard heights would rarely be in this region. In the intermittent and continuous flame regions, the air entrainment rates can be seen to vary with about the 0.5 to 1.0 power of the freeboard height.

Ideally, it would be possible to adjust the freeboard height to suit each particular fire. Mechanically, this is difficult to do, although testing is sometimes done by elevating the test article above the floor to diminish an excessive freeboard height.

It is sometimes necessary to have quite short freeboard heights to be able to collect all the products. If the collection hood becomes located close to the fire, there is the concern that it will enter into radiative exchange with the fire. If the hood has to be treated as a radiating body, then the assumption of free-air burning breaks down. The original NBS furniture calorimeter used a hood with a short freeboard height. To avoid the re-radiation problems, a water-cooled skirt solution was adopted. The lower portions of the hood were made with water-cooled panels, where cooling water flows prevented them from reaching temperatures significantly above ambient.

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